PHASE II – JUST-IN-TIME MAINTENANCE OF NUCLEAR POWER PLANTS

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Just-In-Time Maintenance of Nuclear Power Plants

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Overall Project Goal

The goal of this project is to develop and demonstrate the feasibility of a new technology for maintenance engineering: a Just-In-Time Maintenance (JITM) system for rotating machines. The JITM system is based on several key developments at Texas A&M over the past ten years in emerging intelligent information technologies, which if integrated into a single system could provide a revolutionary approach in the way maintenance is performed. Rotating machines, such as induction motors, range from a few horse power (hp) to several thousand hp in size, and they are widely used in nuclear power plants and in other industries. Forced outages caused by induction motor failures are the reason for as much as 15% - 40% of production costs to be attributable to maintenance, whereas plant shutdowns caused by induction motor failures result in daily financial losses to the utility and process industries of $1 M or more. The basic components of the JITM system are the available machine sensors, that is electric current sensors and accelerometers, and the computational algorithms used in the analysis and interpretation of the occurring incipient failures. The JITM system can reduce the costs attributable to maintenance by about 40%, and it can lower the maintenance budgets of power and process plants by about 35%, while requiring no additional sensor installation. As a result, the JITM system can improve the competitiveness of US nuclear utilities at minimal additional cost.

Summary of Overall Project Approach

As the electric utility industry is rapidly entering an era of deregulation, the survival of the nuclear generating units will highly depend upon their continued profitability. Minimizing and ultimately eliminating unplanned outages, and extending the time period between planned (or maintenance) outages can greatly enhance the economic performance of a nuclear power plant. In fact, in order to enhance their profitability some nuclear utilities are already contemplating to extend the nuclear fuel cycle from 18 months to 24 months. In electric power generation the failure of critical equipment like turbines, generators, motors, fans, and pumps costs millions of dollars in reduced output, emergency maintenance costs, and lost revenues. The utility industry’s response to this risk has been to invest heavily in preventive, and more recently in predictive, maintenance. The importance of detecting problems and preventing failure is reflected in the fact that in many nuclear power plants 15 - 40 % of production cost is allocated to maintenance. Maintenance cost is, in fact, one of the highest controllable operational cost. A more reliable predictor of the maintenance requirements of critical machines would save nuclear utilities hundreds of millions of dollars per year in loss of revenues during downtime, overtime costs associated with emergency repairs, and disrupted generation schedules. A *Just-In-Time Maintenance* (JITM) system is what is envisioned by our team. Such a breakthrough technology might, perhaps, enable nuclear utilities to operate at sufficiently high profitability levels for a competitive power market, deferring a further down-turn in the industry.

Just-In-Time Maintenance Technology: JITM means taking a piece of equipment off-line for servicing when it needs it, rather than according to a fixed schedule. It is expensive and time consuming to shut down critical machines like motors, generators, pumps, fans and turbines for maintenance, so plant operators would like to be sure that the equipment needs servicing before they schedule it. Today, maintenance schedules are based on manufacturer's test data. Of course, no two machines are alike, so fixed maintenance schedules sometimes result in shutting down a machine before it really needs it, or in continuing to operate one that should be overhauled.

Prior federal research funds have been used to develop a novel neural network, as well as a neural network-based application that can detect incipient faults in motor-pumps at very early stages. The purpose of this motor-pump fault diagnosis system was to avoid the catastrophic failure of motors and pumps during power plant operation, and to provide operational data on demand to schedule preventive maintenance. Current industry standard diagnostic procedures are based on expert systems, or statistical studies that use idealized operational parameters as a guideline and are neither adaptable to individual machines, nor can they "learn" to identify the reason that roughly defined operational parameters have been exceeded. Tests on motor-pump data show that our algorithms, in fact, are not only able to predict failure with a high degree of confidence, but can also provide an operator with specific information as to what is wrong. This integrated neural network diagnostics system approach may represent a breakthrough in machine diagnostics because of the technology's ability to "learn" the operational characteristics of individual machines, and because the neural network can pinpoint the problem.

Phase II Objectives

The objectives of the Phase II part of the project, as defined in the tasks of the original project proposal, with start dates and duration, are as follows:

1. ***Assemble the Hardware and Software for the Prototype System:*** Integrate the transducers, data network, data acquisition equipment, the computer and the appropriate software (6/1/99, 6 months),
2. ***Test the Prototype on the Motor Testbed:*** Collect operating data, train the neural networks, and test the JITM technology on induction motor faults, such as broken rotor bars, eccentricity, and bad bearings, etc. (6/1/99, 6 months),

Objectives Accomplished in Phase II

The objectives set-forth in the Phase II part of the proposed project proposal will be accomplished by May 31, 2000.

Summary of Significant Research Results

In this section we summarize the most significant research results of the Phase II effort.

Assembling of the Hardware and Software for the Prototype System

As a result of the hardware set-up design performed during Phase I of the project, the hardware and software for the prototype system is being assembled. The hardware specifications of the prototype system are as follows:

Motor System:

- Three horsepower induction motor, 220V/2Φ/60 Hz, high efficiency totally enclosed motor.
- The motor is fitted with an electrical enclosure providing access to each motor lead. The leads are connected to a 3-phase voltage source for single speed operation. For variable speed operation, the motor wiring is rerouted through a speed controller system.
- The end belts are removed and an independent, adjustable bearing support is provided at each end to secure the rotor. This enables one to introduce parallel and angular misalignment from end-to-end. Of course, the small rotor to stator air gap restricts the amount of permissible misalignment. The bearings are replaceable so that simulated bearing faults can be introduced.
- The rotor is replaceable so that a defective rotor such as poor balance, broken rings and bow can be introduced.

- The stator is secured to the motor housing, which the machine frame will support. The simulation of winding defects such as shorted end-turns and stator sag is possible.
- Provision has been made to mount transducers on the bearing supports and the stator housing for vibration studies. Tri-axial acceleration readings will be obtained at both bearing housings.
- A rigid motor support system is provided.

Controller:

- A standard industrial quality inverter is provided to permit speed changes.
- Relocating leads on a terminal block permits powering the motor directly from a three-phase voltage source or from the controller. The same terminal block can be used to access voltages and currents on all three phases.
- Additionally, the IMMC243 C00 (DSP board with TMS320F243, programmed with communication monitor) board is available for use in variable speed experiments.
- The DMCD Pro (Digital Motion Control Developer, Debugger) environment is provided to make programming of the speed controller more user-friendly.
- C-Compiler Assembler Linker is also available for the same purpose.
- Finally, a 115 VAC/3 phase and 20 A amplifier compatible with IMMC243 C00 is available.

Torque Sensor Mountings:

- Torque sensor mounting hardware is available. (The sensor is like a small motor requiring design and fabrication of the mounting hardware).
- Also, two torque sensor compatible couplings are available.

Rotor Deck:

- An encoder with a mounting bracket is attached to the rotor module.
- Two precision machined split block bearing housings for mounting rolling element bearings are available.
- Two squeze-locked rolling element bearings are available for easy axial adjustments.
- One 5/8" diameter precision turn ground and polished steel shaft is available.
- Two balanced rotors with provisions for altering mass moment of inertia, balance conditions, and capability to be slid along shaft to any desired location are provided.
- Calibrated misalignment study hardware is provided.

- Precision machined rigid rotor base plate with provision to allow for five different rotor span lengths and 10 different configurations is provided.
- Finally, a rigid rotor deck support system is available.

Gearbox:

- One double reduction parallel shaft Gearbox Dynamics Simulator is available, fitted with rolling element bearings and spur gears.
- Also gearbox mounting hardware is available.

Pump:

- One single stage open vane centrifugal pump is provided so that it can be attached to either the rotor deck shaft or gearbox output shaft. The design allows one to remove the gearbox completely, if desired.
- The pump includes a reservoir, two pressure gauges, a 4 to 20 mA modulating control valve, one reservoir shutoff valve, oversized quick disconnects with integral check valves, flowmeter, and associated piping/tubing. The user provides the input from a PLC or equivalent to operate the control valve. By restricting the suction side of the pump, the user introduces typical cavitation phenomena.
- The pump wet-end is fitted with an extra clear cover so that the user can visualize the condition of the fluid stream such as cavitation and turbulence.
- The pump working fluid is water.

Safety Cover and Foundation:

- One impact resistant transparent safety cover is provided to cover the torque sensor and rotor deck area. Additional guards are provided to cover the remaining exposed rotating components.
- The foundation system consists of one common rigid precision machined cast aluminum base with two axial stiffening channels and rubber isolators.

The instrumentation consists of the following items:

- Eight triaxial accelerometers with cables, 6.5 kHz bandwidth,
- One torque sensor including full signal conditioning and analog output,
- One encoder with 1024 pulses per revolution resolution,
- RPM sensor,

- Three current clamps,
- Three voltage clamps,
- Shaft alignment kit, and,
- Shaft straightness kit.

A schematic diagram of the hardware components of the prototype system is depicted in Figure 1.

Preliminary Motor Fault Diagnosis Results

A few selected results are presented here based on the research conducted during Phase II of the project. To demonstrate the JITM concept and the feasibility of model-based diagnosis, accurate motor response predictors have been developed. The developed predictors are tested with three different conditions: balanced supply, 2.5 % power supply unbalance, and insulation failure with 5 out of 138 turns (~4 %) bridged by a 1.5 ohm resistor. The outputs from the three neural predictors are used with the current measurements to generate the residuals. Furthermore, the symmetrical component transforms of the residuals are produced. Finally, the negative sequence voltage is obtained from the measurements of three terminal voltages. The negative sequence of normalized residuals defined as the ratio of negative sequence residuals to negative sequence voltage is used as an indicator for incipient stator fault detection. Figure 2 compares the standard stator fault indicator, that is the negative sequence of the normalized measurements, with the indicator used in this study, the negative sequence of the normalized residuals. For a power supply with low unbalance both indicators are acceptable. As supply unbalance is introduced, one of the indicators shows the existence of a fault, whereas the model-based indicator is still unaltered. The third phase in the figure demonstrates the presence of a stator fault and the response of both indicators. Use of the model-based indicator can potentially eliminate false alarms due to supply unbalance, while maintaining the indicator sensitivity to incipient stator faults at the early stages of failures.

Field Trial Preparations

In view of the Phase III task on field trials, Task 8, the following items have been purchased by Texas Utilities, at no cost to the project:

- One PCI-MIO-16E-1 Multifunction PCI Board functioning at 1.25 Msamples/sec, 12 bit, 16 channels,
- One SCXI-1349 Shielded Cable Assembly, 1 m,

- One SCXI-1000 4-slot Chassis,
- Two SCXI-1141 8 channel Programmable Elliptic Low Pass Filters,
- Two SCXI-1304 terminal block,
- Two SCXI-1305 AC/DC coupling BNC terminal block,
- One data acquisition computer with a network interface card, and,
- One copy of the full LabVIEW Development environment for Windows NT/98/95.

The total cost of this equipment is approximately $12,500. During Phase III of the project the equipment will be installed for field testing of the JITM system developed in this project.

Project Related Accomplishments

Graduate Student Theses and Dissertations

The following graduate dissertations are being pursued with funds from this project:

1. R. M. Bharadwaj, "Adaptive Nonlinear State Filtering for Electric Machine Speed Estimation," PhD Dissertation, in progress.
2. H. Kim, "Model-Based Fault Diagnosis of Electric Machines Using Neural Networks," PhD Dissertation, in progress.
3. S. Nandi, "Fault Analysis of Electric Machines for Condition Monitoring," PhD Dissertation completed, March 2000.

Journal Papers

The following journal publication has resulted from research that is related to this project:

1. Nandi, S., H. A. Toliyat, and A. G. Parlos, "Performance Analysis of a Single-Phase Induction Motor Under Eccentric Conditions," submitted to the IEEE Transactions on Industry Applications, August 1998.

Conference Papers

The following conference publications have resulted from research that is related to this project:

1. Kim, K., and A. G. Parlos, "Model-Based Fault Diagnosis of Electromechanical Systems Using Dynamic Recurrent Neural Networks," 7th Mechatronics Forum International Conference, Atlanta, Georgia, September 6-8, 2000.
2. Parlos, A. G., K. Kim, and R. Bharadwaj, "An Early Warning System for Diagnosing Incipient Machine Failures Using Recurrent Neural Networks and Other Intelligent Signal Processing Methods," COMADEM 2000, Houston, Texas, December 10-12, 2000.
3. Nandi, S, R. Bharadwaj, H. A. Toliyat, and A. G. Parlos, "Simulation of a Three Phase Induction Motor with Incipient Rotor Cage Faults," Proc. of the IEEE International Conference on Diagnostics for Electrical Machines, Power Electronics, and Drives, Dijon, Spain, September, 1-3, 1999.

4. Bharadwaj, R, A. G. Parlos, and H. A. Toliyat, "Adaptive Neural Networks-Based State Filter for Induction Motor Speed Estimation," Proc. of the 1999 IEEE Industrial Electronics Society Annual Meeting, San Jose, CA, December 1999.
5. Bharadwaj, R, A. G. Parlos, H. A. Toliyat, and S. K. Menon, "A Neural Network-based Speed Filter for Induction Motors: Adapting to Motor Load Changes," Proc. of the International Joint Conference on Neural Networks, Washington, D.C., June, 1999.
6. Bharadwaj, R, A. G. Parlos, H. A. Toliyat, and S. Nandi, "A Neural Network-based Speed Filter for Induction Motors: Adapting to Motor Condition Changes," IEEE International Conference on Diagnostics for Electrical Machines, Power Electronics, and Drives, Dijon, Spain, September, 1-3, 1999.

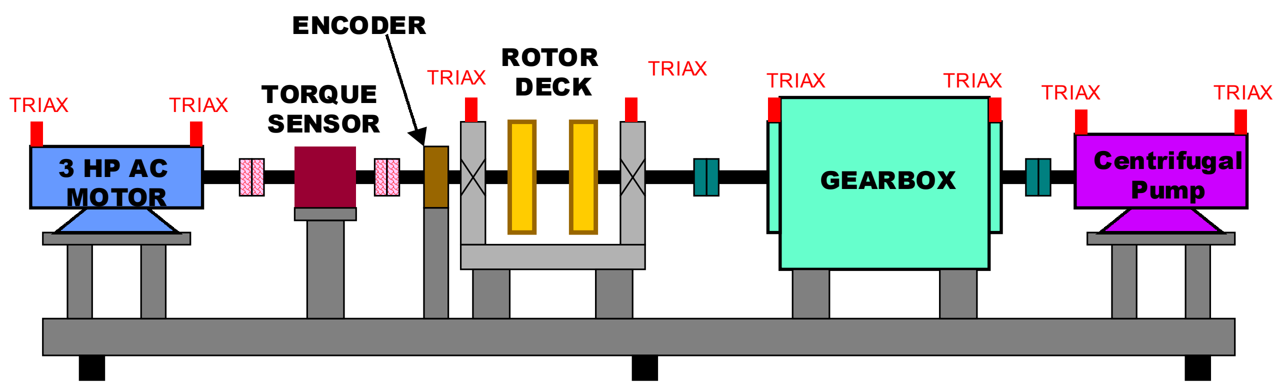

Figure 1. Hardware Configuration for Prototype Fault Diagnosis System.

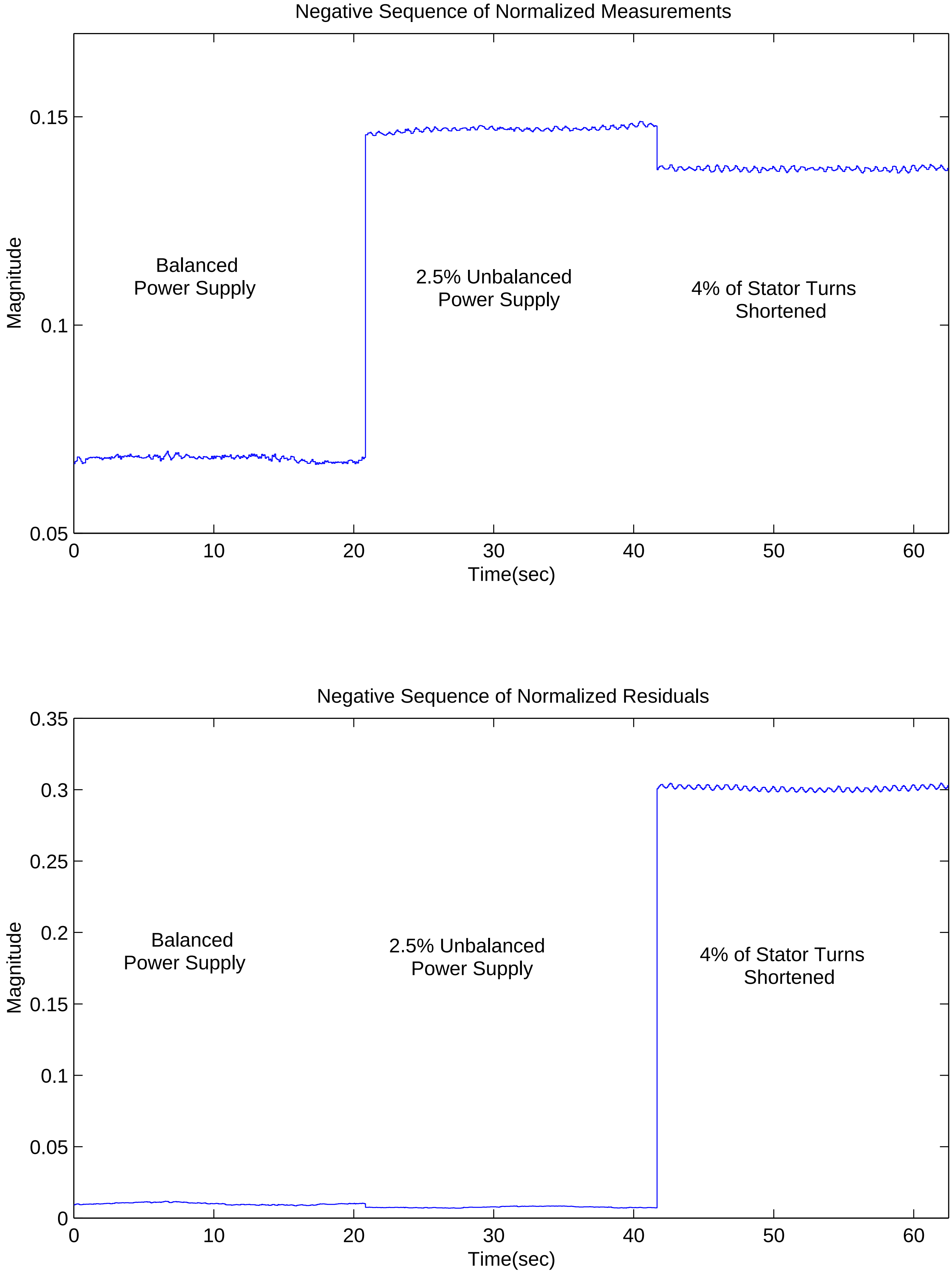

Figure 2. Neural network speed filter response for two rotor broken bars scenario.